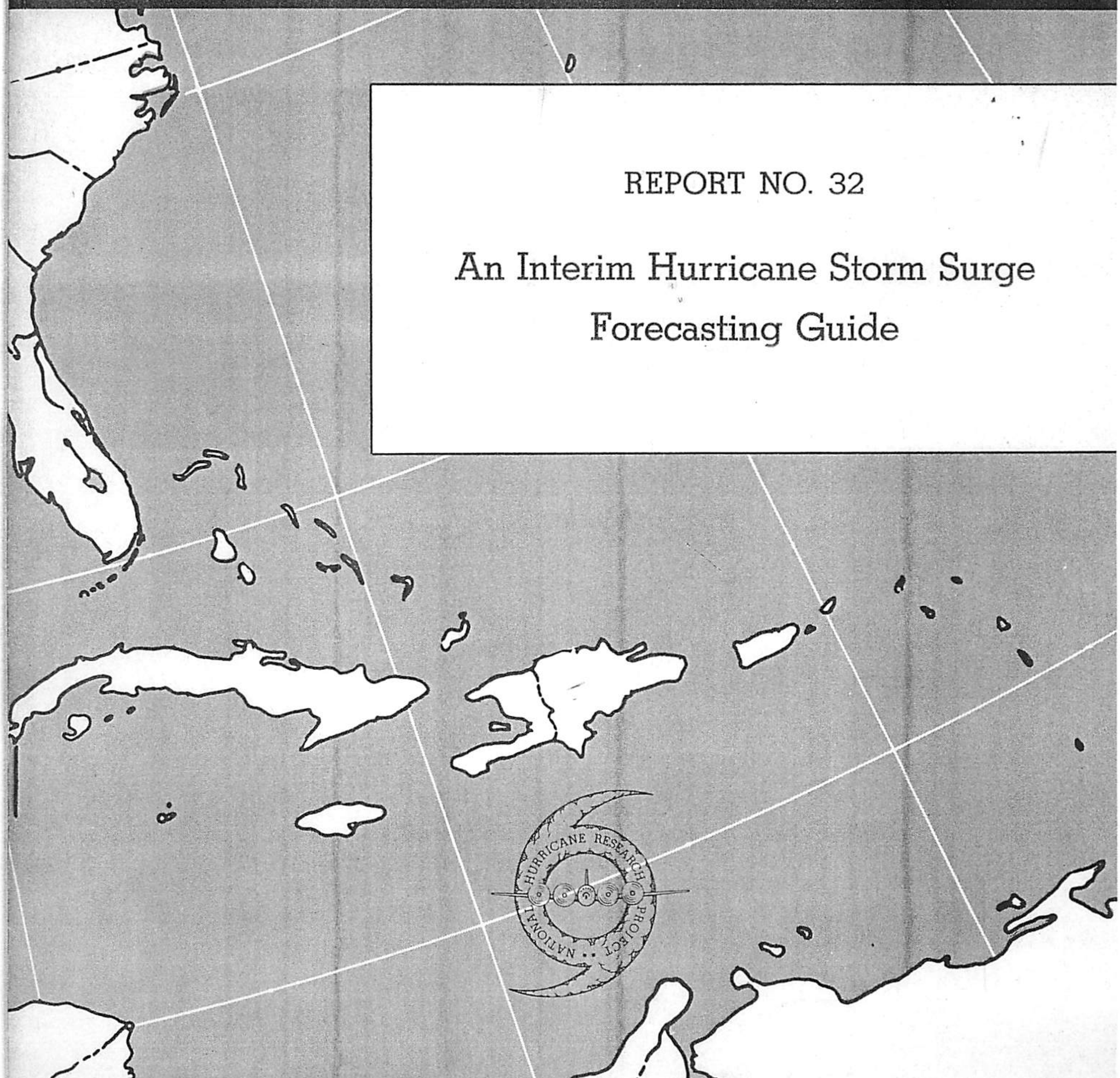
NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 32

An Interim Hurricane Storm Surge Forecasting Guide



U. S. DEPARTMENT OF COMMERCE
Frederick H. Mueller, Secretary
WEATHER BUREAU
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NATIONAL HURRICANE RESEARCH PROJECT

REPORT NO. 32

An Interim Hurricane Storm Surge Forecasting Guide

by

D. L. Harris

U. S. Weather Bureau

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NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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TABLE 1. --HURRICANE PARAMETERS FOR STORM SURGE STUDY

Number	Date	P_o	h	Datum	SLA	h*	Δp	R	S	c	θ	DPS	Location of peak tide
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	1893 - 10 - 1	956	9.3	MSL	M	9.3	60	17	75	7	52 L	L 12	Deer Island (Near Biloxi) Miss.
2.	1894 - 9 -27	986	5.3	AN	M	5.3	M	M	51	M	21 L	Ov.Sta.	Charleston, S.C.
3.	1900 9 8	936	14.6	MSL	M	14.6	73	14	98	10	68 R	R 10	Galveston, Texas
4.	1901 8 14	973	7.4	MSL	M	7.4	48	33	79	14	70 L	R 39	Mobile, Alabama
5.	1906 9 27	965	10.8	MSL	M	10.8	53	57	26	16	68 R	R 59	Fort Barrancos, Florida
6.	1909 7 21	959	10.0	MSL	M	10.0	66	19	98	12	62 R	R 20	Galveston, Texas
7.	1909 9 20	980	6.0	MSL	M	6.0	46	88	48	11	62 R	L 19	Timbalier Island, La.
8.	1910 10 18	959	10.3	MSL	M	10.3	49	48	130	11	74 R	R 18	Everglades, Florida
9.	1912 9 13	993	4.4	MSL	M	4.4	M	M	79	M	48 R	R 8	Mobile, Alabama
10.	1915 8 17	949	13.9	MSL	M	13.9	55	28	107	11	80 R	R 65	High Island, Texas
11.	1915 9 29	938	9.0	MSL	M	9.0	83	26	36	10	80 R	R 13	Grand Isle, La.
12.	1916 7 5	961	4.7	MSL	M	4.7	56	50	51	25	76 R	R 37	Fort Morgan, Alabama
13.	1916 10 18	974	3.0	MSL	M	3.0	49	44	26	21	82 L	R 8	Pensacola, Florida
14.	1917 9 28	964	7.1	MSL	M	7.1	48	31	26	13	28 L	Near	Fort Barrancas, Florida
15.	1919 9 9	929	6.6	MSL	.1	6.5	78	15	8	8	30 R	R 13	Key West, Florida
16.	1921 10 25	958	11.0	MSL	.1	10.9	44	18	101	10	36 R	R102	Punta Rassa, Florida
17.	1926 8 25	959	10.0	MSL	.2	9.8	69	27	48	10	90	R 38	Timbalier Bay, La.
18.	1926 9 18	934	10.5	MSL	.1	10.4	82	24	6	17	82 L	Near	Miami Beach, Florida {Same Storm}
19.	1926 9 20	955	9.4	MSL	.4	9.0	65	24	26	7	36 R	R 13	Pensacola, Florida
20.	1928 9 16	935	9.8	AN	.1	9.7	94	28	2	13	51 L	L 8	West Palm Beach, Florida
21.	1929 9 28	953	8.8	MSL	0	8.8	66	28	7	10	48 R	Near	Key Largo, Florida
22.	1933 8 23	970	7.0	AN	.4	6.6	28	54	75	18	15 L	R 14	Hampton Roads, Virginia
23.	1933 9 5	949	13.0	MSL	M	13.0	75	30	40	8	79 R	L 15	Brownsville, Texas
24.	1934 7 25	975	5.9	MSL	M	5.9	M	M	98	M	38 R	R 80	Galveston, Texas
25.	1935 11 4	973	9.3	MSL	.3	9.0	M	M	6	M	46 R	R 15	Miami Beach, Florida
26.	1936 7 31	964	6.0	MSL	0	6.0	52	19	43	9	54 R	R 37	Panama City, Florida
27.	1938 9 21	943	14.6	AN	.1	14.5	57	50	63	47	80 L	R 6	Moriches, New York
28.	1940 8 7	974	4.8	MSL	.1	4.7	34	11	109	8	32 R	R 24	Calcasieu Pass, Louisiana
29.	1940 8 11	975	8.5	AN	.5	8.0	42	26	69	12	71 L	L 5	Beaufort, South Carolina
30.	1941 9 23	959	9.9	MSL	1.4	8.5	45	21	56	13	68 L	L 16	Sargent, Texas
31.	1941 10 7	981	6.4	MSL	.3	6.1	41	18	116	11	64 L	R 19	St. Marks, Florida
32.	1942 8 30	951	14.8	MSL	.8	14.0	53	18	59	14	87 R	R 9	Matagorda, Texas
33.	1943 7 27	975	4.0	MSL	.4	3.6	42	17	98	8	59 R	L 12	Galveston, Texas
34.	1944 9 14	959	7.8	AN	.1	7.7	36	26	116	30	50 L	R 33	Newport, Rhode Island
35.	1944 10 19	962	11.0	MSL	.4	10.6	42	34	130	14	47 R	R48	Naples, Florida
36.	1944 10 20	991	4.4	AN	.4	4.0	M	M	51	M	27 L	R 17	Charleston, South Carolina
37.	1945 8 27	968	7.3	AN	.9	6.4	52	18	59	4	38 L	R 7	Matagorda, Texas
38.	1947 8 24	992	3.6	MSL	1.1	2.5	M	M	106	M	38 R	R 50	Sabine Pass, Louisiana
39.	1947 9 17	940	9.8	MSL	.3	9.5	70	19	2	10	90	Near	Hillsboro Beach, Florida
40.	1947 9 19	966	11.1	MSL	.2	10.9	40	28	75	16	38 R	R 50	Biloxi, Miss.
41.	1947 10 15	968	6.5	AN	.7	5.8	36	13	65	17	45 R	Near	Quarantine Station, Savannah Riv., Ga.
42.	1948 9 4	987	5.6	MSL	.5	5.1	M	M	75	M	68 L	R 46	Biloxi, Miss.
43.	1949 8 26	954	4.2	MSL	.1	4.1	66	22	6	14	59 L	R 28	New Jupiter Inlet, Florida
44.	1949 10 3	963	10.4	AN	1.4	9.0	51	15	74	11	59 L	Near	Freeport, Texas
45.	1950 8 30	979	5.5	MSL	.4	5.1	27	21	26	23	73 L	R 14	Pensacola, Florida
46.	1950 9 5	958	7.2	MSL	.9	6.3	M	M	85	M	47 L	R 25	St. Petersburg, Florida
47.	1954 8 31	961	12.7	AN	.3	12.4	M	45	71	33	60 L	R 43	Sakonnet Point, R. I.
48.	1954 10 15	937	13.0	AN	.2	12.8	64	18	54	26	55 L	R 25	South Port, North Carolina
49.	1955 8 17	986	6.0	AN	.6	5.4	M	M	57	M	76 L	L 7	Holden Beach, North Carolina
50.	1955 9 19	966	6.0	AN	.5	5.5	46	50	59	9	37 R	R 11	Morehead City, N. C.
51.	1956 9 24	974	7.4	AN	.3	7.1	36	29	42	20	30 L	R 15	Laguna Beach, Florida
52.	1957 6 27	947	13.9	AN	1.4	12.5	59	19	112	14	80 L	R 22	Calcasieu Pass, Louisiana

P_o = central pressure of the hurricane (mb.)
h = storm surge (ft.)
SLA = seasonal sea level anomaly (ft.)
h* = storm surge adjusted for seasonal sea level anomaly
p = $P_n - P_o$ where P_n is computed as described by Myers [8]. (mb.)
R = radius of maximum winds (n. mi.) (After Myers [10])

S = distance from the shore to the 50-fathom line (n. mi.)
c = speed of the storm (kt.) (From [10])
θ = angle between storm track and the coast; L = land to the left of the storm track, R = land to the right.
DPS = distance of the peak surge right (R) or left(L) of the storm track, measured normal to the track (n. mi.)

AN INTERIM HURRICANE STORM SURGE FORECASTING GUIDE

D. L. Harris
U. S. Weather Bureau

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1. INTRODUCTION

The primary goal of the storm surge program, as of the entire hurricane program, is the safeguarding of life and property with the minimum of inconvenience to the public. Weather Bureau advisories, warnings, and bulletins should lead to the minimum of evacuation and other protective action consistent with all of the protective measures that are really necessary.

It is desirable here to distinguish between two functions: forecasting and warning. In carrying out the forecasting function, one considers the available information on the present and recent state of the atmosphere to determine the future state which he thinks has the maximum likelihood of occurrence. The forecast may suggest alternative possibilities. In performing the warning function, one should begin with the meteorological forecast, recognize its uncertainties, and publish a warning message describing the potential danger clearly enough for those who receive the message to understand what protective action is necessary to avoid loss of life and preventable loss of property.

Techniques for the evaluation of the hurricane storm surge problem necessary for the issuance of effective and efficient warnings are discussed in this paper. The forecasting techniques presented are not in general applicable to extratropical storms.

Four steps may be recognized in a hurricane storm surge warning procedure:

1. Forecasting the hurricane motion and development.

2. Determining the storm tide which is implied by the hurricane forecast.

3. Determining the practical importance of the storm surge in terms of specific flood depths at particular places.

4. Distributing the warning.

Although this report is concerned primarily with steps 2 and 3 some discussion of the present state of the hurricane forecasting art is desirable to furnish background for the main topic. This discussion is given in the following section.

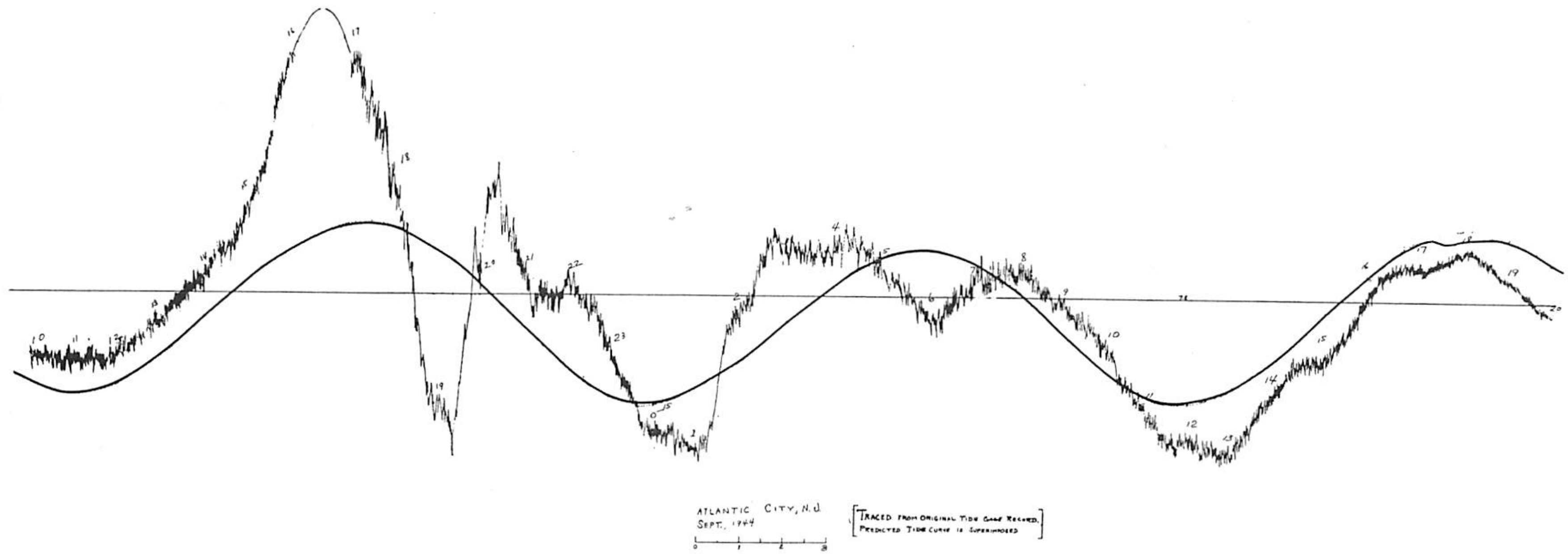

Figure 1. - Observed and predicted tide at Atlantic City, N. J., September 14-15, 1944.

2. THE METEOROLOGICAL FORECAST

The first step in formulating a hurricane storm surge warning is forecasting the future position and intensity of the hurricane. According to the usual practice, the location of the low pressure center is first determined and then the wind field and other features of the storm are related to the position of the center. Gentry [2] verified more than 300 forecasts for 12 and 24 hours made by the Weather Bureau in the 1955-57 seasons. The median position error for all of the 24-hour forecasts was 118 nautical miles and for all 12-hour forecasts was 63 nautical miles. The verifications for the region south of 30°N. latitude and west of about 62°W. longitude were a little better, being 93 nautical miles for the 24-hour forecasts and 51 nautical miles for the 12-hour forecasts. These figures are comparable with all of the unpublished verifications known to the author. It appears that an uncertainty of approximately 50 miles in the forecast location of the storm center must be anticipated for each 12 hours of a 24-hour forecast period in the development of a warning system. The actual uncertainty in a particular case may be greater or less than this figure and may or may not be indicated by the forecast.

This uncertainty concerning the future motion of the storm limits the amount of resolution one is justified in attempting in the storm tide forecast.

3. THE HURRICANE HIGH WATER

The most deadly feature of the hurricane is the storm high water. It is pertinent to point out some of its major characteristics before considering forecast techniques and warning procedures. The actual tide record and the predicted astronomical tide at Atlantic City during the hurricane of September 14-15, 1944, are shown in figure 1. The hurricane center passed off the coast about 30 miles to the east of the tide station. The great irregularity of the tide height, with superimposed oscillations having periods from a few minutes to several hours, is typical of the few first class tide records obtained near hurricane centers. The cause of these oscillations has not been definitely established; however there is no good reason for believing that their peak value is recorded at the tide station. Figure 2, after Harris [5], shows a group of high water marks left by Hurricane Audrey, 1957. Notice that the differences of 2 to 3 feet in the peak value were recorded within distances of only a few miles. Some of these points were surveyed a second time to make sure that the differences were real. The original values were verified. Similar irregularities exist in the records showing a sufficiently dense network of high water marks for other hurricanes. These differences appear to be the result of small-scale variations in local topography or irregularities in the hurricane wind field, or both.

In view of the uncertainty in the hurricane position forecast, no effort to take these small-scale topographic features into account appears to be justified at the present time.

The storm high water may be considered as the sum of three components of widely different scales:

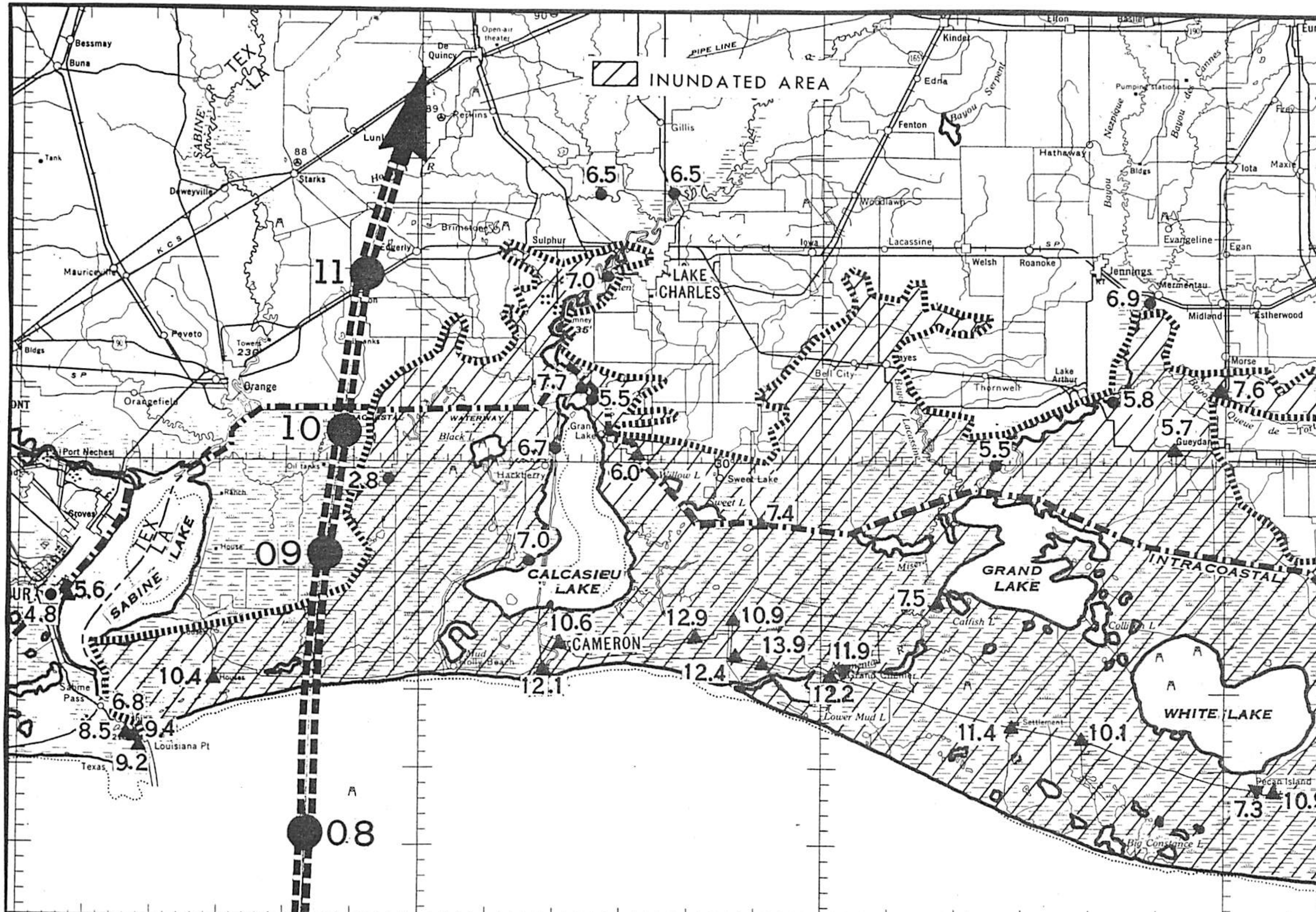

Figure 2. - High water marks obtained near the center of hurricane Audrey, June 1957. (From [5])

1. The storm surge which is generated by the high winds, decreased pressures, and high seas of the storm. In the empirical work described below, the storm surge is taken as the difference between the observed tide and the sum of the seasonal and secular anomalies in sea level and the astronomical tide.

2. The seasonal and secular anomalies in sea level.

3. The astronomical tide resulting from the variations in the gravitational attraction of the sun and moon.

Each of these must be considered in composing a hurricane storm tide warning. Techniques for doing so are discussed below.

4. THE HURRICANE STORM SURGE

The need for an estimate of the storm surge to be expected from a particular hurricane has been widely recognized. Techniques for making an estimate have been published recently by Conner, Kraft, and Harris [1]; Hoover[6]; and Reid [9]. For maximum usefulness the estimation technique should be simple, and it should be based on storm parameters that are obtainable before the storm crosses the coast. Coast and Geodetic Survey and Corps of Engineers records as well as Weather Bureau files have been systematically examined to find data which could be used in developing and testing such techniques. An attempt has been made to correct the observed data for the stage of the astronomical tide whenever sufficient information was available. If the correction could not be applied, the data were referred to mean sea level in regions having a mean tide range of 2.5 feet or less and rejected elsewhere. Records which are believed to give a reasonable estimate of the peak storm surge were found for 52 hurricanes or tropical storms. These records and other pertinent data are given in table 1.

It has been found (Harris [5]) that seasonal anomalies in sea level may account for a significant portion of the storm high water in a hurricane. These anomalies may arise long before the hurricane comes into existence and may last long after the storm has passed. It appears that their effect should be added to that of the storm, or conversely their effect as well as that of the astronomical tide should be removed from the observed tide record in estimating the effect of the storm. The difference between observed and predicted monthly mean sea levels for the month of the storm was used as an estimate of the seasonal anomaly in sea level. A mean for two months was used if the storm occurred near the end of a month. This correction has been derived for most of the data after 1919, and was used in the statistical work described below.

The storm surge prediction equation, when stripped to its basic essentials, takes the form

$$h \propto \frac{V^2 L}{D} \tag{1}$$

where: h = storm surge
V^2 = effective wind stress directed toward the shore
L = length of the fetch
D = depth of the water

This suggests that the storm surge should be the product of three functions, one depending on the wind speed, one on the fetch length, and one on the depth of the water.

It is to be assumed that V in equation (1) refers to some type of average wind speed, and this cannot be measured with any great accuracy, especially before the storm comes inland. However, we know that this should be related to the pressure gradient. The central pressure, p_o, can be obtained before landfall of the hurricane by use of dropsondes and other aircraft observations (Jordan [7]). Thus we may replace V^2 by the pressure deficiency $(p_n - p_o)$ if a suitable estimate for p_n, the pressure outside the hurricane, is available. Two methods of defining p_n have been tested: one is a tabulation of p_n, as defined by Myers [8], and the other is the determination of a constant value of p_n by a least squares fit of the data to an equation of the type

$$h = b(p_n - p_o) \tag{2}$$

where b and p_n are arbitrary constants determined by the data.

A test involving the 44 storms given in table 1, for which data of the type described by Myers were available, showed that a higher correlation was obtained by using the constant p_n.

It is not clear from the above whether L should refer to the size of the storm or to some geographic factor. In the statistics described below, the radius of maximum winds (indicated by R below) as described by Myers [8] and given in table 1 was used as a measure of the size of the storm.

The depth of the water is always a variable, and usually increases with distance from the shore, so this must be expressed by some parameter involving the slope of the continental shelf. Several parameters were tested. No other parameter was more objective or more effective than the distance between the shore and the 50-fathom depth contour, indicated by S below. The distance to the 10-fathom and the 100-fathom contours were nearly as satisfactory.

The 44 cases for which p_n and R, as tabulated by Myers were available, were fitted to equations of the type

$$h = b\,(p_n - p_o)^{\alpha}\, S^{\beta} \tag{3}$$

and

$$h = b\,(p_n - p_o)^{\alpha}\, S^{\beta}\, R^{\gamma} \tag{4}$$

where b, α, β and γ are constants to be determined by the data.

Equation (2) gave a correlation coefficient of 0.637. This was increased to 0.711 by equation (3) and 0.719 by equation (4). The final improvement is considered insignificant and an equation of the form of (3) is recommended.

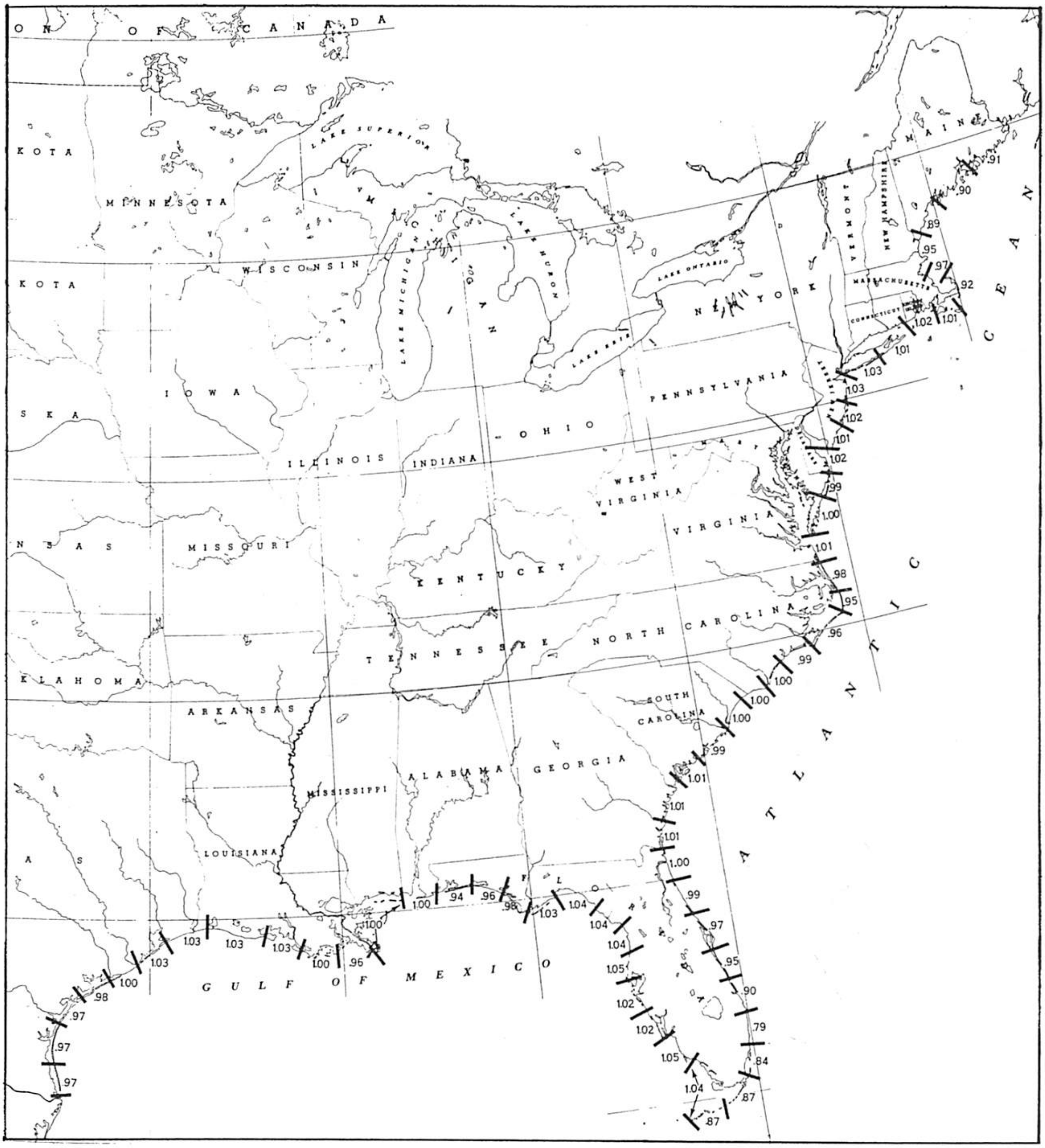

Figure 3. - Map showing relative storm surge potential Θ of various coastal sections. (See text)

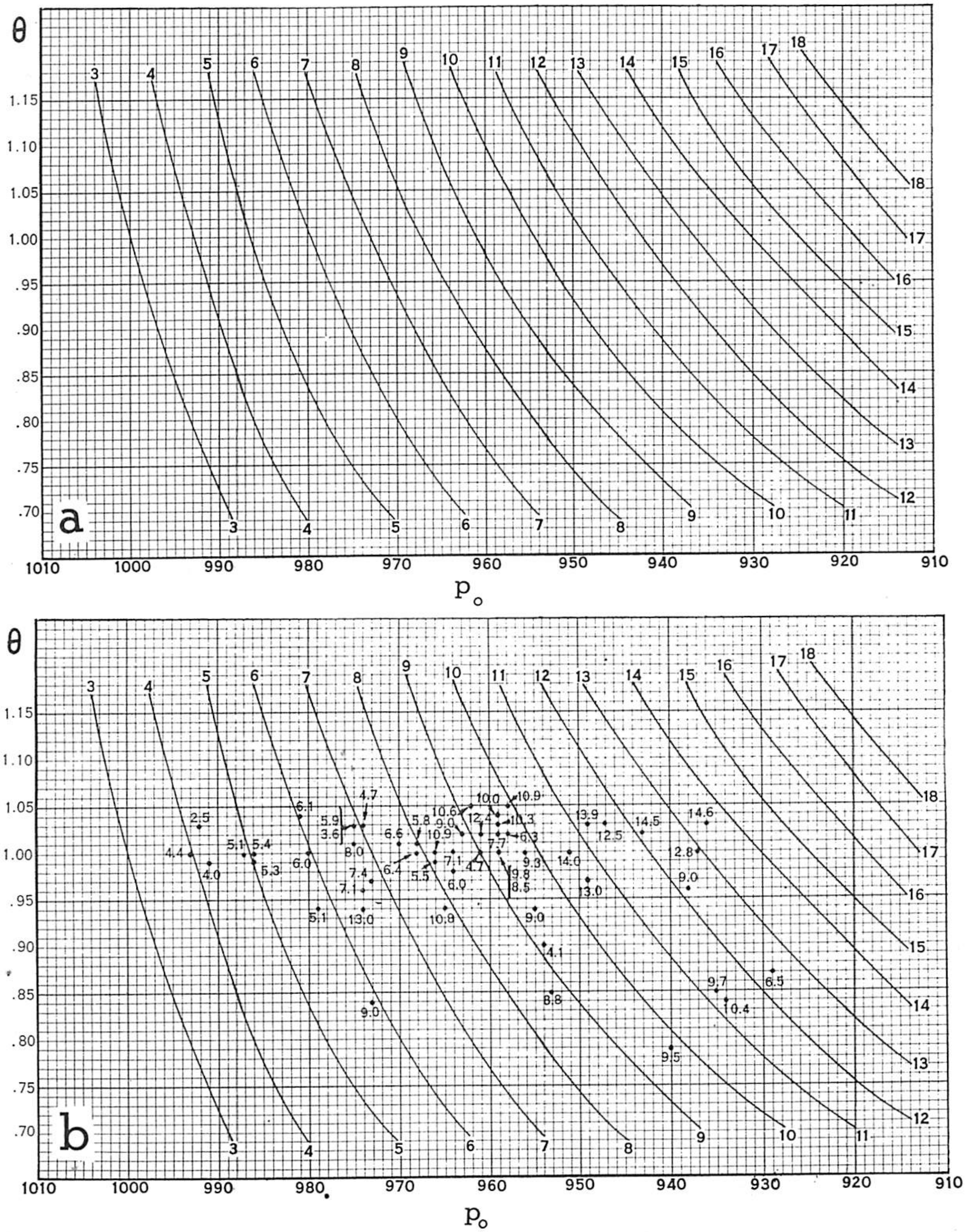

Figure 4. - (a) Storm surge prediction chart. (b) Prediction chart including dependent data.

This is fortunate, since the parameter R is difficult to determine while the storm is still at sea, and if R and variable p_n are neglected, all 52 storms can be used to determine the operational prediction equation.

The resulting equation takes the form

$$h = 0.06213\,[1025 - p_o]^{1.1328}\,S^{0.0663} \tag{5}$$

with a standard error of 2.1 feet and a correlation coefficient of 0.75. It is interesting to examine the data represented by equation (5) when it is plotted in the form:

$$h = \theta f(p_o) \tag{6}$$

Where θ is a fraction, near unity, which depends on the offshore depths and $f(p_o)$ is a function of the central pressure. Figure 3 shows values of θ for the Atlantic and Gulf Coasts of the United States. Figure 4a shows isolines of storm surge on the chart whose ordinates are θ and p_o. The data from table 1 are superimposed on this chart in figure 4b.

Equation (5) was used to compute the estimated storm surge for each of the 52 storms in table 1, and the differences between the observed and computed storm surges were plotted as functions of p_o, p_n, R, speed of the storm, the angle at which the storm crossed the coast, and on maps showing the storm tracks. No systematic variations with any of these variables were disclosed.

The average distance from the storm track to the peak reported surge was 20 miles, and 2/3 of the cases fell between 5 miles to the left and 35 miles to the right. But the extreme cases were 20 miles to the left and 100 miles to the right. No correlation between the location of the peak surge relative to the storm track and any other readily identified features of the coastline or storm was discovered. The uncertainty relative to the location of the peak storm surge should be recognized when composing the warning message.

The forecast method outlined above is applicable only to hurricane and tropical storms. The nature of the storm surge undergoes a drastic change as the storm becomes extratropical in character. This is well illustrated by the records for the hurricane of October 19, 1944, shown in figures 5a and 5b.

Hourly values of the storm surge, for several Atlantic coast tide stations, and the storm track are shown in figure 5a. The line running diagonally across the storm surge curves indicates the time at which the storm center was nearest each tide station. Several synoptic maps during the life of the storm are shown in figure 5b.

In the region of hurricane landfall, and elsewhere along the coast, when the right hand side of the hurricane passes over water the peak storm tide generally occurs within an hour or two of the lowest pressure (Harris [4]). If the hurricane moves approximately parallel to the shore, but over land so that the tide station is to the right of the track, the peak surge may precede the lowest pressure by several hours as shown for the southern stations in figure 5a.

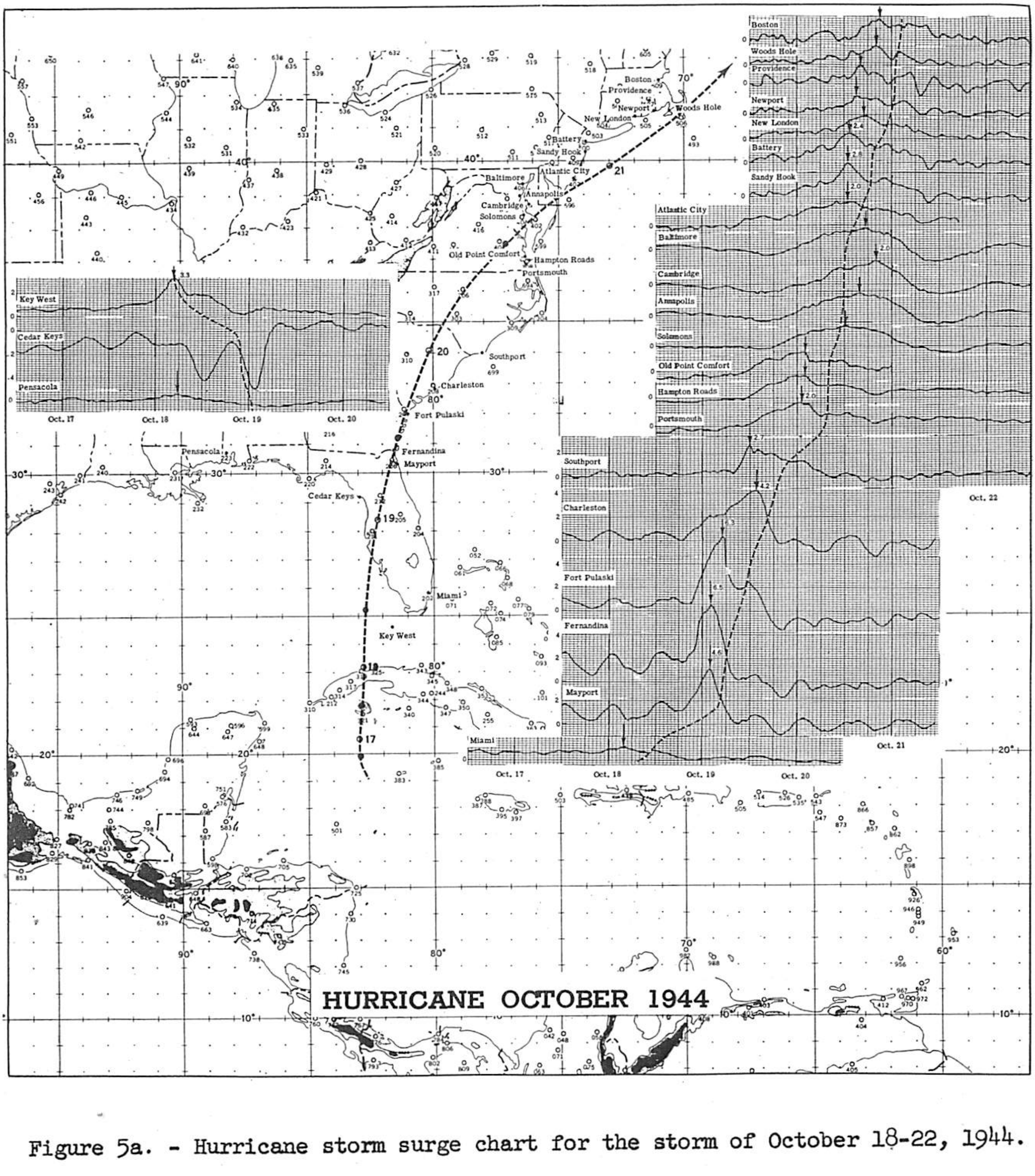

Figure 5a. - Hurricane storm surge chart for the storm of October 18-22, 1944.

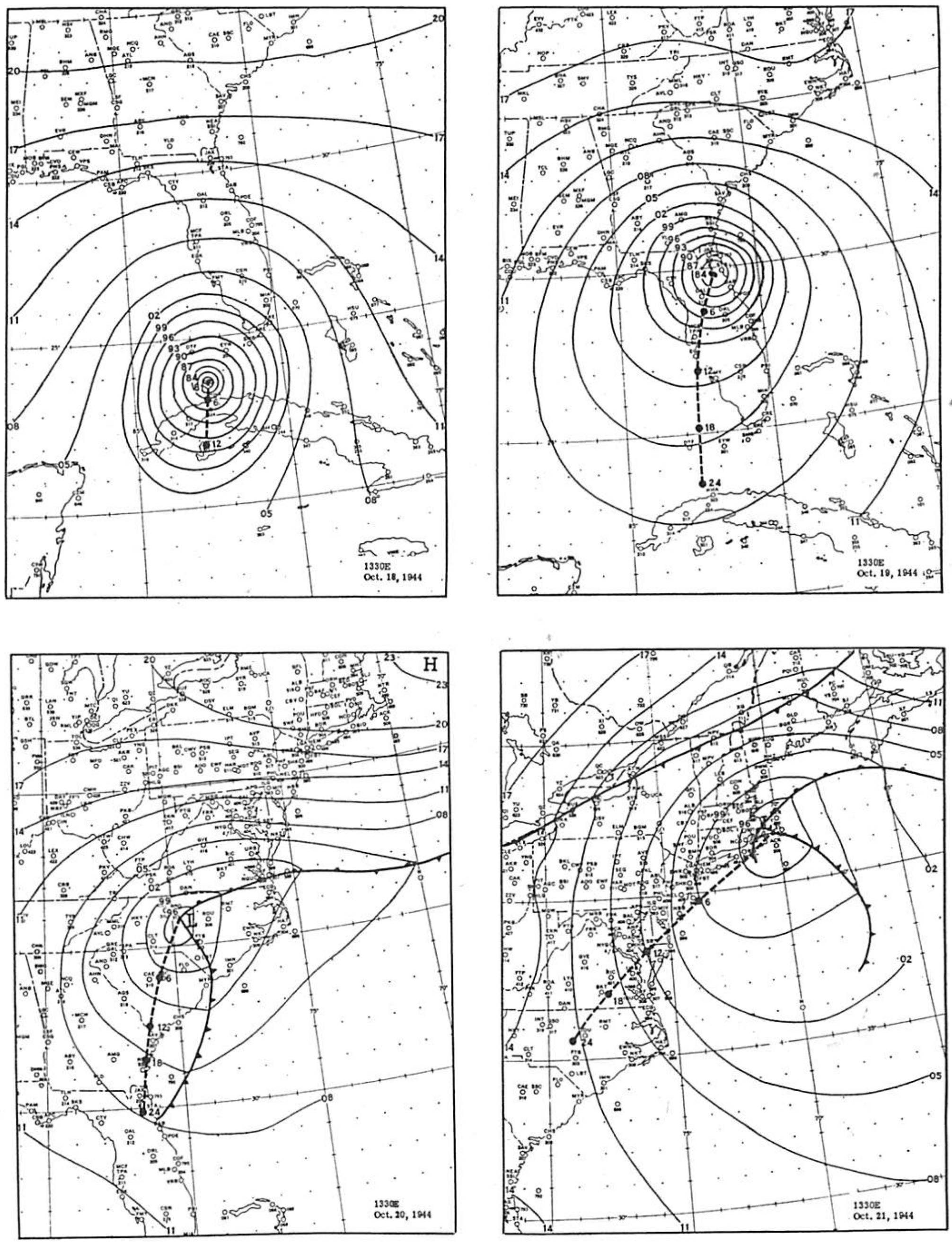

Figure 5b. - Synoptic maps of the storm center at 1330 EST, October 18-21, 1944.

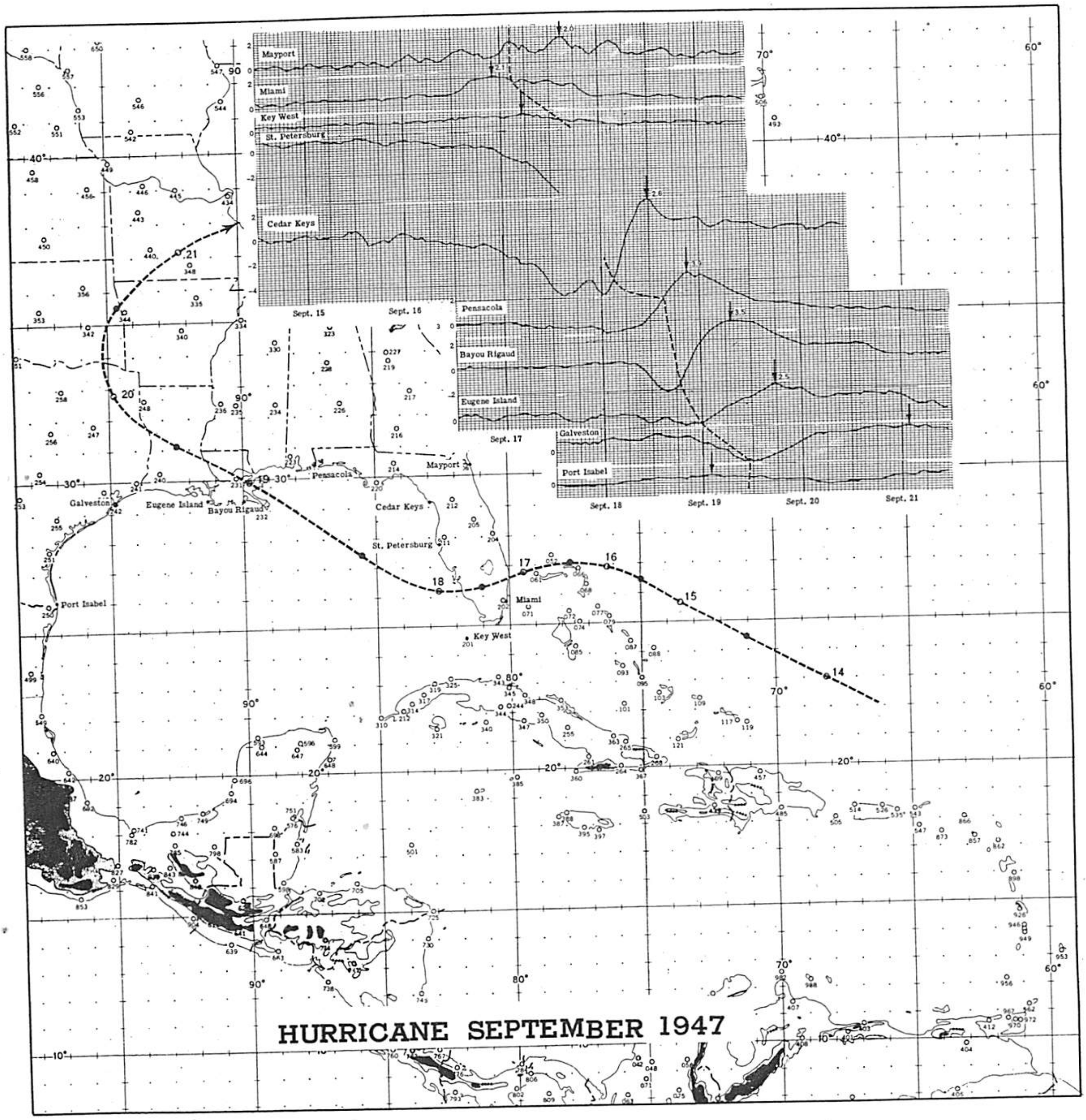

Figure 6a. - Hurricane storm surge chart for the storm of Sept. 15-20, 1947.

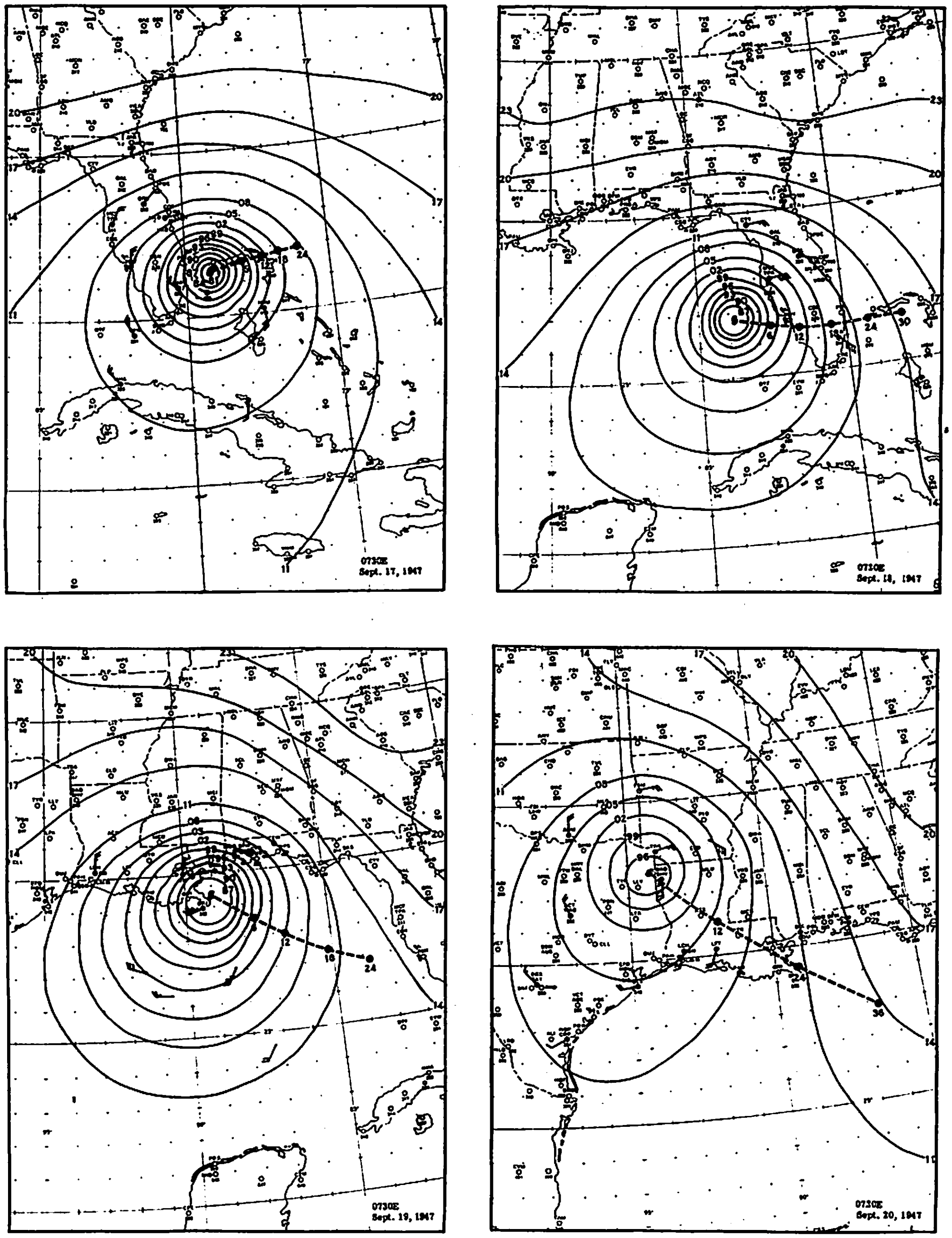

Figure 6b. - Synoptic maps of the storm center at 0730 EST, Sept. 17-20, 1947.

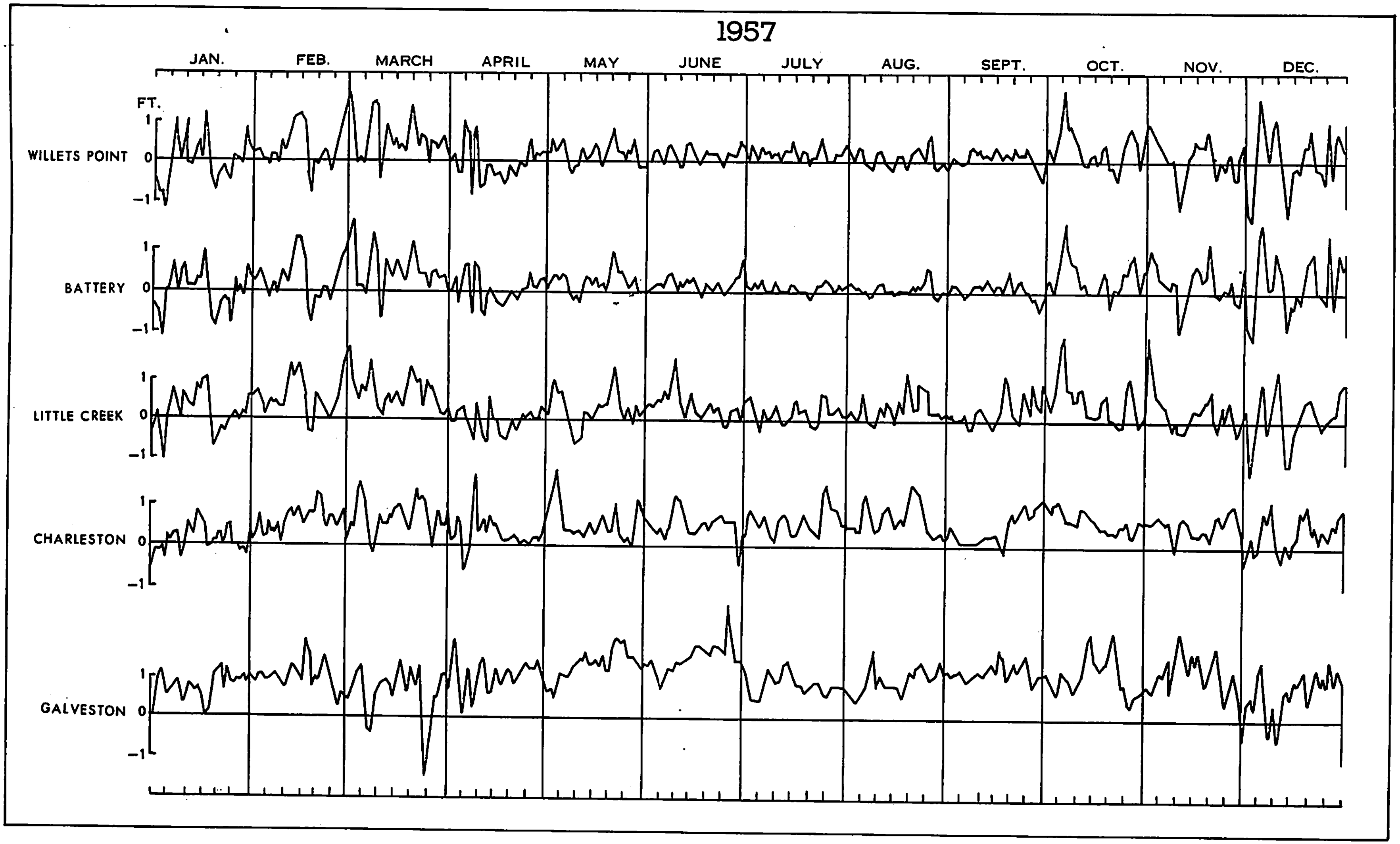

Figure 7. - Departure of the observed daily mean sea level from the predicted value for selected Coast and Geodetic Survey tide stations in 1957.

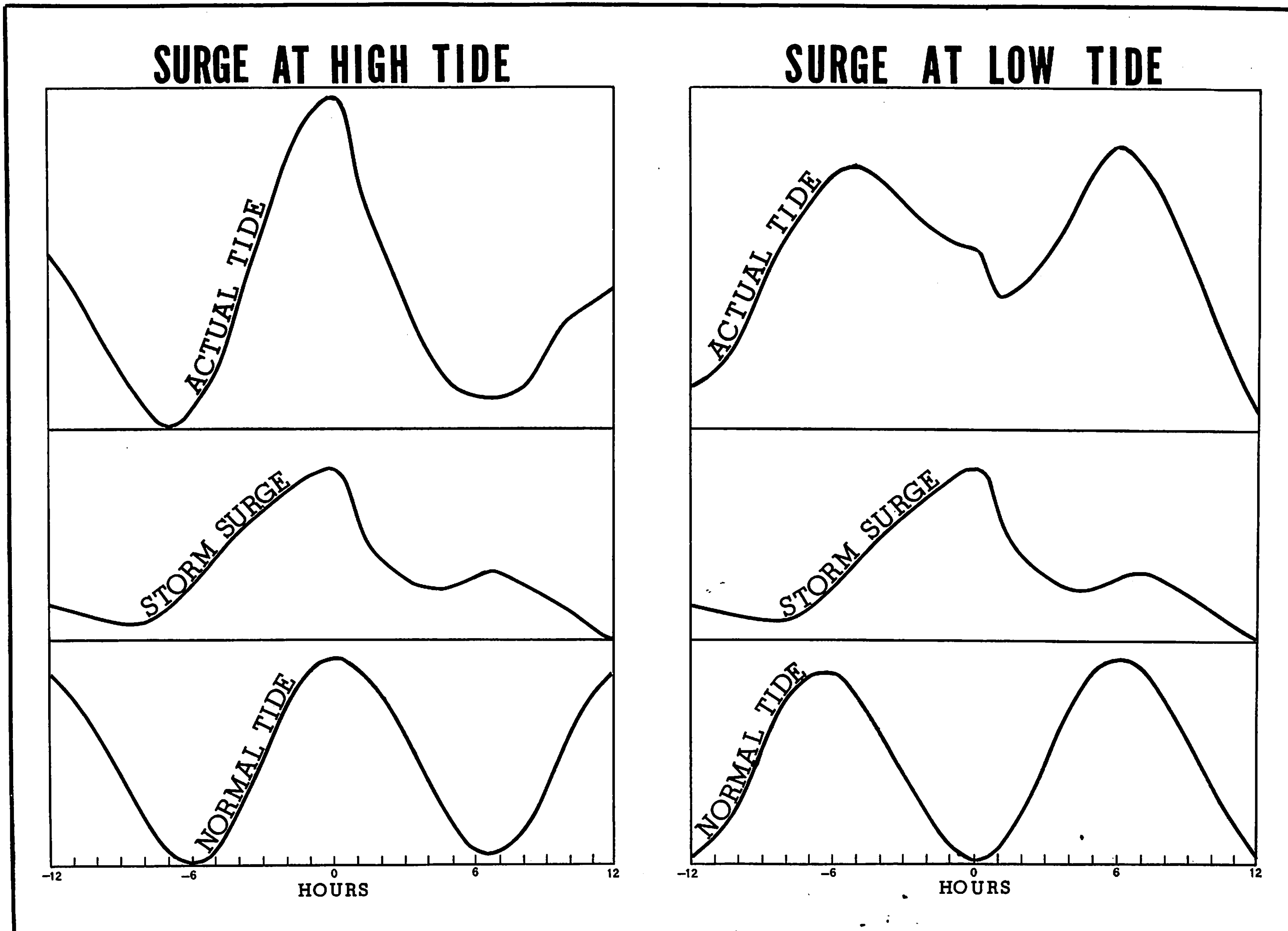

Figure 8. - Relative effects of identical storm surge superimposed on astronomical tide at high and low water.

The storm surges produced by the hurricane of September 17-19, 1947, shown in figures 6a and 6b, are typical of those in which the hurricane moved over water a considerable distance, with the shore to the right of the hurricane track. In this case the storm surge was negative until after the passage of the lowest pressure, and the peak storm surge occurred several hours later.

5. SEASONAL AND SECULAR VARIATIONS IN SEA LEVEL

It has been shown (Harris [5]) that the daily mean sea level may differ from the seasonal average value by a foot or more for several weeks at a time. Insofar as a hurricane is concerned, these variations would appear as changes in sea level. In the absence of intense storms, this component of the tide varies rather slowly and it appears that the average departure of the daily mean sea level from its predicted value for the 4 or 5 days preceding a hurricane would give a good estimate of this quantity and should be added to the results obtained from figure 4a to obtain the forecast for the storm surge.

The Coast and Geodetic Survey has cooperated in establishing remote recording tide gages at 14 Atlantic and Gulf Coast stations, and several more are planned for the fall of 1959. Hourly predictions of the astronomical tide are furnished to those stations having remote recorders to facilitate the determination of the difference between observed and predicted tide.

The differences between the observed and predicted astronomical tide at 0000, 0600, 1200, and 1800 EST are transmitted as a part of the synoptic report by those weather stations having remote tide recorders. The average value of the four departures for each day of 1957 at several stations is shown in figure 7. The average of four consecutive 6-hour values is used to eliminate any unevenness which may be due to temporary phase shifts between the actual and predicted tide, and any failure of the tide prediction formula to reproduce the shape of the tide curve equally well throughout the tide cycle. The daily average obtained in this way correlates well with that obtained by taking the average of the 24 hourly values during the day. It is much simpler as a part of an operational program than the use of any of the numerical filters described by Groves [3].

6. ASTRONOMICAL TIDE

The astronomical tide is an important component of many storm high waters. That this is so can be readily seen from figure 8, which shows the effects of combining the identical storm surge with the normal tide at different phases of the normal tide.

The astronomical tide at several Gulf of Mexico tide stations for a 15-day period is shown in figure 9. Notice that three distinct types of tide regimes are illustrated. Two distinct high and low waters occur on each lunar day at Key West and St. Marks River Entrance. Two high and low waters can be recognized for each day at Tampa Bay and Galveston, but they can hardly be called distinct. At Pensacola and Mobile, one high and one low occur each solar day. Envelopes of the highs and lows are shown for these two stations. Notice that the diurnal tide range varies from approximately 0.5 ft. to approximately 2.0 ft. within this period.

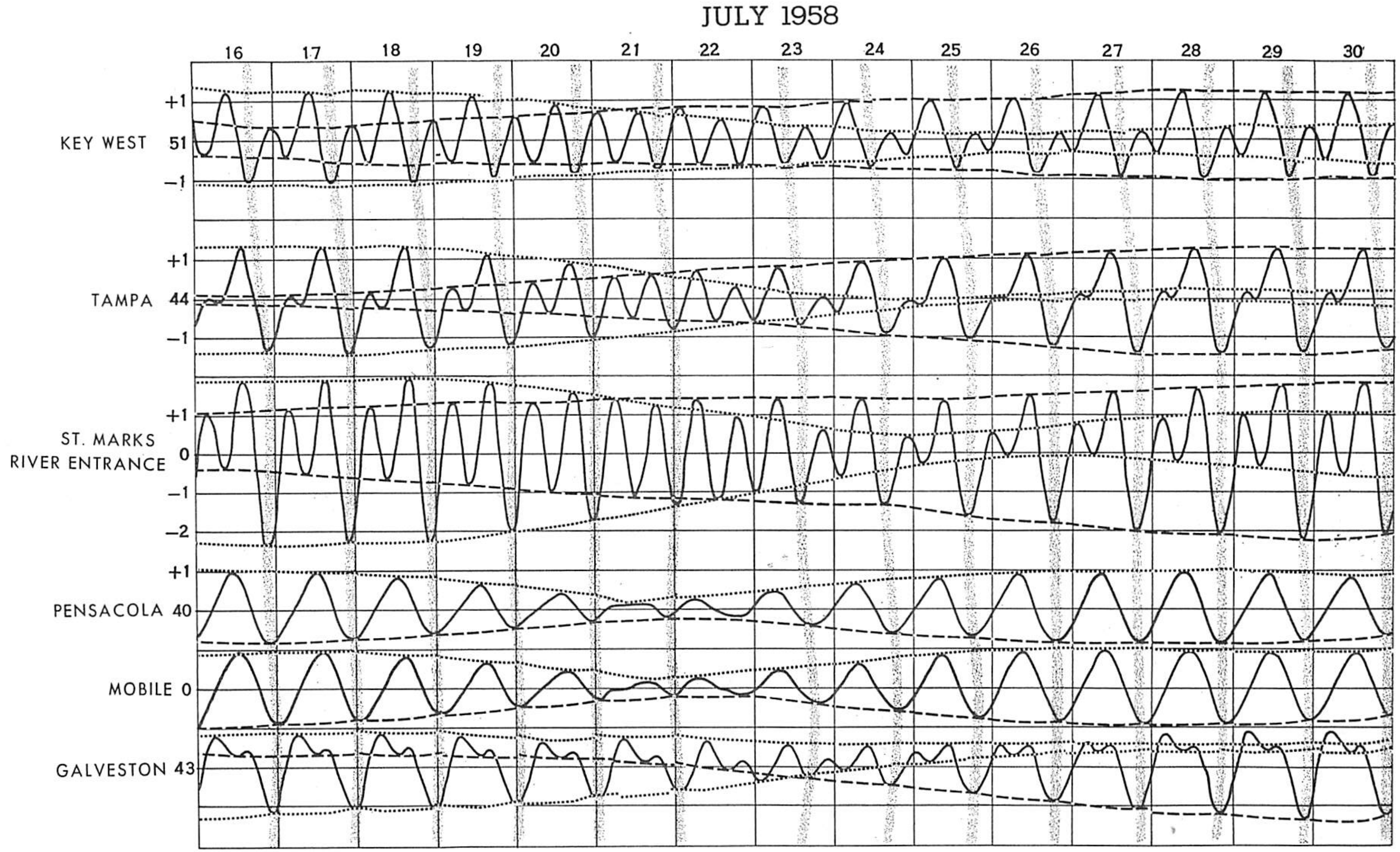

Figure 9. - Astronomical tide predictions for selected Gulf of Mexico harbors, July 16-30, 1958.

At the stations having two high and two low waters each day, envelopes have been drawn connecting alternate highs and alternate lows. Notice that the envelopes which bracket the higher highs and lower lows at the beginning of the period are bracketing the lower highs and higher lows at the end. Notice again that the greatest diurnal range may exceed the least by 2 feet or more, even in the Gulf of Mexico, and that the difference between the two high waters on a given day may exceed 1 foot. Similar differences not shown here, may also occur between two low waters of many days.

It is worthwhile to notice that time continuity can be followed between the lower low water at all stations in the Gulf of Mexico, excepting during the day or two of minimum range when this continuity breaks down. There is a loose time continuity for the other features of the tide curve but this is not so easy to follow. The time continuity among the most significant features of the tide curve is much clearer along the Atlantic Coast.

The variation in range of the astronomical tide is due primarily to three factors:

1. The phase of the moon, with the greater range (spring tide) near new and full moon, and the lesser range (neap tide) at first and third quarters.

2. The declination of the moon, with the greater range (tropic tides) at maximum declination, and the lesser range (equatorial tides) with the moon over the equator.

3. The distance between the moon and earth, with the greater range (perigean tides) with the moon nearest the earth and the lesser range with the moon at its greatest distance from the earth (apogean tides).

Only the first two of these is important in the Gulf of Mexico, and as each of these has a period of approximately two weeks, the principal features of the tide in the Gulf of Mexico can be displayed in a record of only two weeks duration.

The third effect is important on the Atlantic Coast, particularly in New England, and as it has a period near 28 days, a full lunar month is necessary to show all of the major features. The predicted tides for a 30-day period at several Atlantic coast stations are shown in figure 10. Notice that at Boston the neap high tide nearest perigee is nearly 1-1/2 feet higher than the neap high tide nearest apogee.

The range of the tide is greatest when all these factors producing large tide ranges coincide. The variation in the phase relations between these factors may lead to significant variations in the height of the high tide. For example: the predicted daily high water at Boston varied from 8.5 feet MLW on April 23 and other dates to 11.9 feet MLW on September 25 in 1957.

The curves shown in figure 10 were selected to illustrate the variation in range and shape of the tide curve throughout a lunar month and along the coast. Notice in particular the asymmetry of the curve at Woods Hole and the flattened highs and lows in the curve for Willets Point.

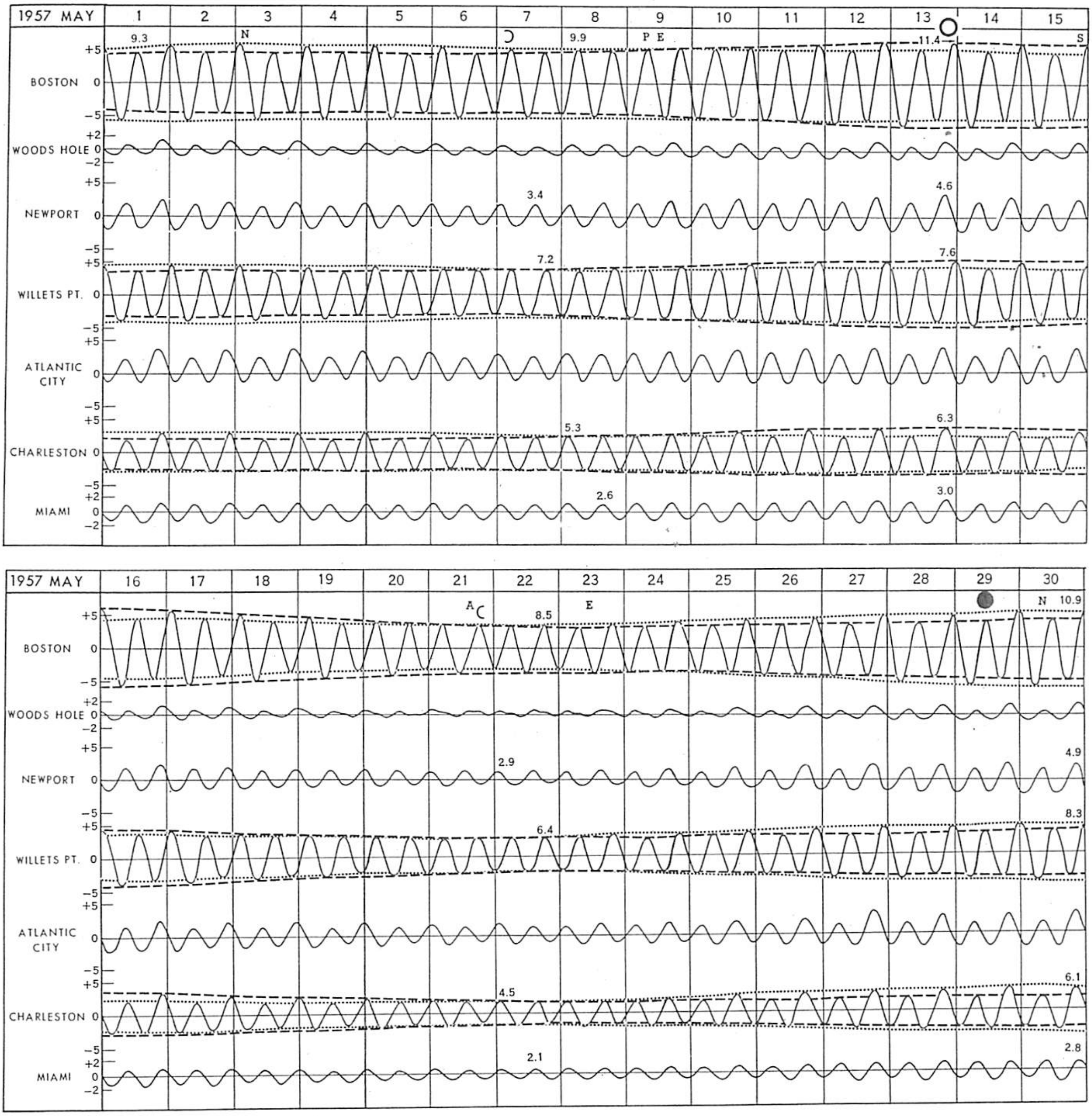

Figure 10. - Predicted tides at selected Atlantic coast stations for May 1957. Envelopes of high and low tides and the actual value of the highest and lowest higher high waters are shown for several stations. The astronomical data are shown as follows: ● New moon;) First Quarter; O Full Moon; (Last Quarter; E, moon on the Equator; N, S, moon farthest North or South of the Equator; A, P, moon in Apogee or Perigee.

Unfortunately, it is often impossible to predict the time of landfall of a hurricane with sufficient accuracy to determine the phase of the tide at the time of landfall. However, it is generally possible to determine the day of landfall 12-24 hours in advance and thus to know the phase of the fortnightly or monthly cycle of tide ranges.

Envelopes of the high tide as shown in figures 9 and 10 are shown in figure 11 for the period June-December 1959 at Charleston, S. C., Miami, Fla., and Pensacola, Fla. The time of the high tide, to the nearest hour, is shown for each fifth or sixth day. Notice the rough correspondence between the high waters at Pensacola and the higher high waters at Charleston. Notice that at Charleston the difference between the height of the highest and lowest high waters for the period illustrated exceeds 2 feet. This difference is smaller in the Gulf of Mexico but still significant in terms of land elevations in inhabited areas. It is greater at many locations north of Charleston. These data suggest that the public should be informed of normal height of the next predicted tide whenever storm tide warnings are issued.

7. IMPORTANCE OF THE STORM HIGH WATER

The practical importance of a given storm high water depends on the elevation of the land, its exposure to wave action, and the land use. The importance of advance warnings depends also on the type of protective action which is either possible or practicable.

The forecaster will be in a better position to issue timely warnings if he fully understands the specific storm surge problems within the threatened coastal area. A program for the preparation of storm surge warning manuals and storm tide warning maps has been started. The planned output of this program is a set of maps on a scale of 1/250,000, similar to figure 12, covering the entire Atlantic and Gulf coastlines. These charts should show generalized 5-ft. contours from the shore to the 25-ft. contour, and critical elevations of highways and bridges within these limits. Each map will be accompanied by a descriptive text, or supplementary tables and figures designed to clarify the storm surge problem for each coastal community. Highlights from this text will be superimposed on the maps as shown. Each map should be planned to give a definitive answer to one specific question, "Which communities, in the area covered by the map, will have significant flooding problems from a storm high water x feet above mean sea level?" In many cases, the maps will provide as much information concerning the nature of this problem and what can be done about it as the forecaster can use. In other cases it may be necessary to refer to the accompanying text for a full description of the problem.

8. SUMMARY

Recent studies of the accuracy of hurricane position forecasts indicate that position errors in excess of 50 miles for a 12-hour forecast or 100 miles for a 24-hour forecast are of frequent occurrence. Such errors are small when compared to the scale of the synoptic map but they seriously limit the amount of detail one is justified in attempting in a storm surge forecast. Studies of the high water marks left by a storm and of tide gage records during a storm also indicate that variations of 2 or 3 feet in the high water marks

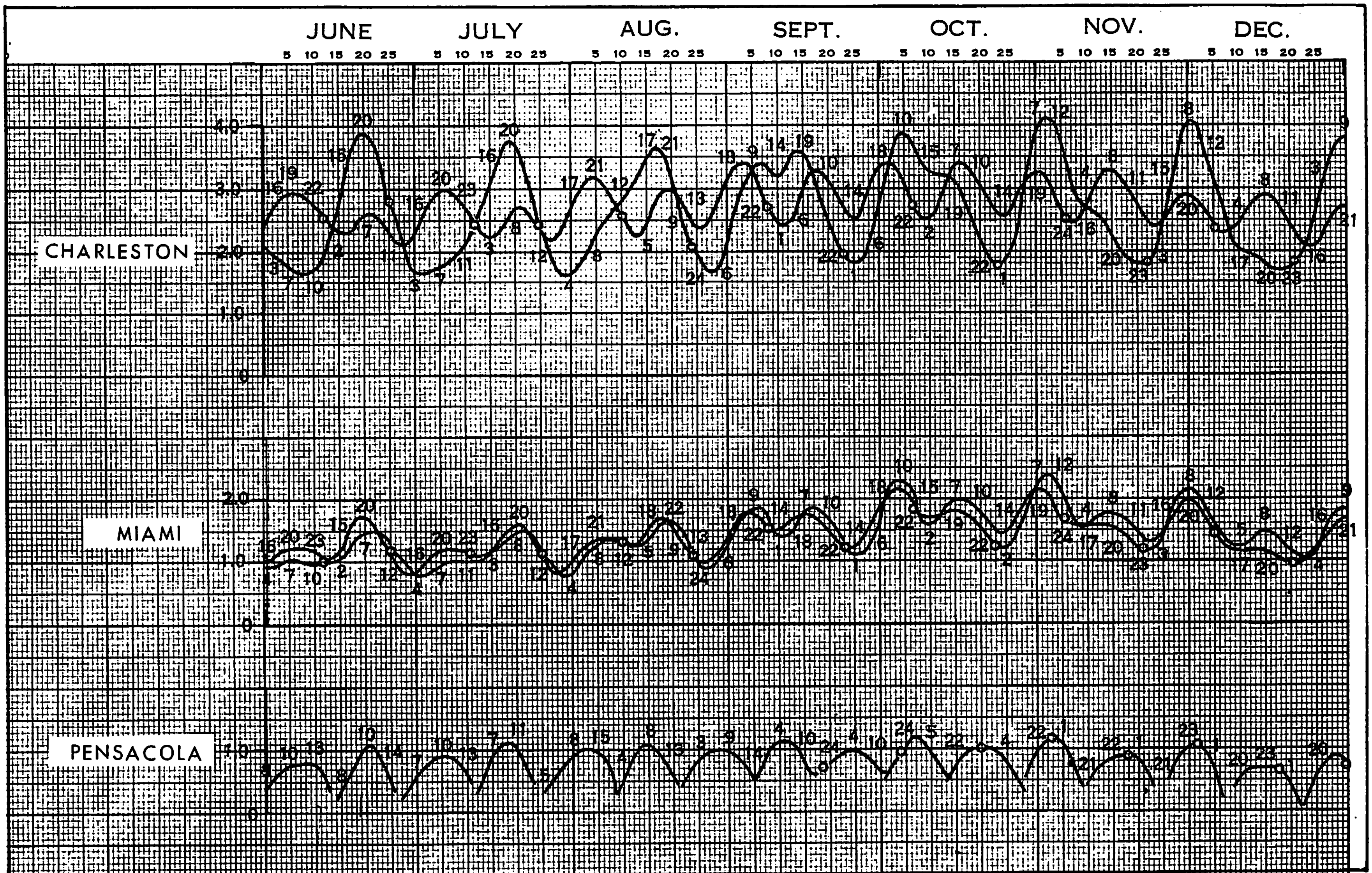

Figure 11. - Envelopes of the predicted high tides at Charleston, S. C., Miami, Fla., and Pensacola, Fla., for June-December 1959.

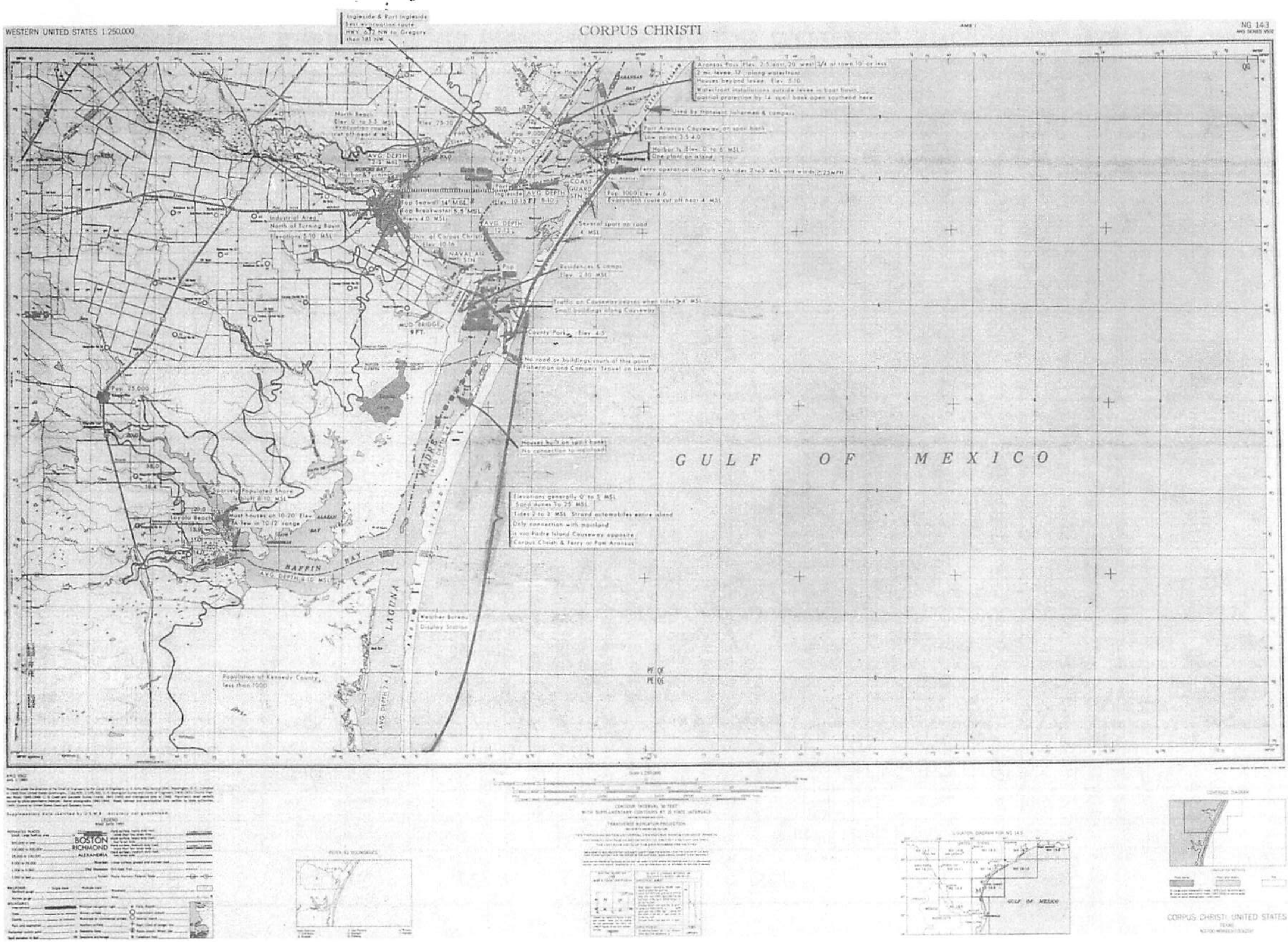

Figure 12. - Sample of proposed charts for improving the storm tide warning service.

within distances of only a few miles accompany many hurricanes. A statistical study of peak storm surge heights generated by past storms indicates that the peak storm surge can be predicted with a standard error of 2.1 ft. from a knowledge of the central pressure of the storm and the distance between the coast and the 50-fathom line.

The importance of the normal astronomical tide and of the timing of the storm surge to the severity of the storm high water is pointed out. At the present time (1959) hurricane position forecasts for 12 hours and longer cannot be made with sufficient accuracy to permit an accurate estimate of the peak storm high water at a particular location 12 hours or more in advance. However it is possible for the forecaster to know the range of the normal tide on the day of the storm, and as this varies considerably throughout the month it is recommended that the predicted height of the normal high tide in the threatened region should be included in local hurricane warnings.

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(Continued from back of title page)

No. 28. A model hurricane plan for a coastal community. March 1959.
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